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BRANCH OF RESEARCH AND LABORATORY SERVICES

INTERNAL REPORT

HELIUM THERMAL CONDUCTIVITY VALUES, 133° TO 740° K, AND
PRANDTL NUMBERS, 130° TO 760° K, FOR PRESSURES TO 300 ATMOSPHERES

By

Robert E. Wood, F. W. Baer, and W. J. Boone, Jr.

APPLIED RESEARCH

Project 7116

February 1971

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BUREAU OF MINES
HELIUM ACTIVITY
HELIUM RESEARCH CENTER
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CONTENTS

	<u>Page</u>
Abstract.	3
Introduction.	4
Low-density thermal conductivity of helium.	5
Dense-gas thermal conductivity of helium.	23
Prandtl numbers of helium	27
Discussion.	35
References.	37

ILLUSTRATIONS

Fig.

1. Low-density thermal conductivity deviation plot for helium.	10
2. Thermal conductivity of helium.	27

TABLES

1. Data distribution and deviation analysis.	25
2. Maximum deviations between computed and experimental thermal conductivities.	26
3. Thermal conductivity of helium	28
4. Prandtl numbers of helium	34

CHAPTER I

The first part of the book is devoted to a general introduction to the subject. It begins with a discussion of the importance of the subject and the scope of the book. It then proceeds to a discussion of the various methods of research and the results of the research. The chapter concludes with a summary of the main points and a list of references.

CHAPTER II

The second part of the book is devoted to a detailed discussion of the various methods of research. It begins with a discussion of the various types of research and the results of the research. It then proceeds to a discussion of the various methods of research and the results of the research. The chapter concludes with a summary of the main points and a list of references.

HELIUM THERMAL CONDUCTIVITY VALUES, 133° TO 740° K, AND
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Robert E. Wood^{1/}, F. W. Baer^{2/}, and W. J. Boone, Jr.^{3/}

ABSTRACT

The temperature dependency of the low-density thermal conductivity coefficients, λ_T° , of helium, 100° to 1,200° K, is correlated with a third degree polynomial.

The equation $\lambda_{T,P} = \lambda_T^\circ + \alpha \left[\left(\frac{\partial P}{\partial T} \right)_V \right]^\beta$, where α and β are least-squares parameters, represented 385 experimental higher pressure thermal conductivity values of helium in the temperature range 126.55° to 831.15° K for pressures to 504.32 atmospheres, with a mean absolute deviation of 0.79 percent. This equation was used to tabulate thermal conductivity values of helium for 47 pressures, 1 to 300 atmospheres, and 110 temperatures, 133° to 740° K.

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Isobaric heat capacity, C_p , and viscosity, η , values from previous work were combined with the thermal conductivity, λ , values to compute Prandtl numbers, $C_p \eta / \lambda$, of helium. Tabular values of the Prandtl numbers are presented for 49 pressures, 1 to 300 atmospheres, and 15 temperatures, 130° to 760° K.

Estimated uncertainties in tabulated values are ± 5 percent for the thermal conductivity coefficients and ± 10 percent for the Prandtl numbers.

INTRODUCTION

Engineers charged with helium purification equipment design and evaluation require a knowledge of the thermophysical properties of helium. Low-pressure thermal conductivity values of helium over a wide range of temperatures are fairly abundant, and most of the available data have been systematically analyzed and compared. However, high-pressure thermal conductivity data are of a research nature and require correlation to be of value to engineers.

This report presents a method for the general correlation and prediction of thermal conductivity values of compressed helium gas as an aid to heat transfer calculations applicable to gas-to-gas heat exchanger design and evaluation. The temperature dependency of the low-density thermal conductivity values of helium for the temperature range 100° to 1,200° K is correlated with the equation

$$\lambda_T^\circ = 311.70 + 4.474T - 1.632 \times 10^{-3} T^2 + 5.0076 \times 10^{-7} T^3, \quad (1)$$

microjoules/(centimeter second degree Kelvin), and the effect of pressure on the thermal conductivity behavior of helium is generalized by the equation

$$\lambda_{T,P} = \lambda_T^\circ + 146.7635 \left[\left(\frac{\partial P}{\partial T} \right)_V \right]^{0.8289516}, \quad (2)$$

where $\lambda_{T,P}$ = thermal conductivity of compressed helium, $\mu\text{j}/\text{cm sec } ^\circ\text{K}$,

λ_T° = thermal conductivity of dilute helium,

and $\left(\frac{\partial P}{\partial T} \right)_V$ = thermal pressure coefficient, $\text{atm}/^\circ\text{K}$.

Equation 2 was used to compute thermal conductivity values of helium for 47 pressures, 1 to 300 atmospheres, and 110 temperatures, 133° to 740° K.

Isobaric heat capacity, C_p , (32)^{4/}, viscosity, η , (34), and the

^{4/} Underlined numbers in parentheses refer to items in the list of references at the end of the report.

thermal conductivity, λ , values calculated in this work were used to compute Prandtl numbers of helium for 49 pressures, 1 to 300 atmospheres and 15 temperatures, 130° to 760° K.

LOW-DENSITY THERMAL CONDUCTIVITY OF HELIUM

The Thermophysical Properties Research Center, Lafayette, Indiana, has collected, organized, and compiled (to 1966) experimental low-density thermal conductivity data for helium from 41 sources. From the available data, TPRC produced a table of recommended thermal

conductivity values of helium for the temperature range 0.08° to $5,000^{\circ}$ K. The TPRC values are those now recommended by the National Standard Reference Data System of the National Bureau of Standards (24).

Discrepancies exist between the measurements of different workers, and deviation plots (24) show deviation in experimental data relative to TPRC's recommended values in excess of 8 percent for the temperature range 100° to 700° K. In the temperature range 100° to 400° K, most of the data fall within a deviation band of ± 4 percent. However, Powell, Ho, and Liley (24) have assessed the accuracy of the TPRC recommended thermal conductivity values to be 1 percent for temperatures from 100° to 400° K, and 5 percent for temperatures from 400° to 700° K. TPRC's recommended thermal conductivity values of helium were selected so as to agree with the higher temperature data, to 579° K, of Kannuluik and Carman (16). Powell and coworkers (24) say that this selection agrees with the trend of the considerably higher temperature data of Blais and Mann (2) ($1,200^{\circ}$ to $2,000^{\circ}$ K) and of Peterson and Bonilla (23) (306° to $1,268^{\circ}$ K).

The selection of Kannuluik and Carman's (16) higher temperature data by both TPRC and NBS for the recommended thermal conductivity values of helium and the assessment of 1 percent accuracy (24) for the recommended values in the temperature range 100° to 400° K are puzzling.

Tsederberg (28) has found fault with Kannuluik and Carman's selection of a large diameter wire for their hot-wire type thermal conductivity apparatus because large diameter wires require large radiation corrections. Radiation corrections of 1, 3, 8, and 20 percent for measurements at 0° , 100° , 218° , and 306° C, respectively, are cited by Kannuluik and Carman (16). Such significant corrections reduce the reliability and accuracy of the thermal conductivity measurements.

Vargaftik and Zimina (31) have attempted to correct the measurement of several investigators who either ignored or judged as negligible the temperature jump effect in their thermal conductivity determinations. Kannuluik and Carman (16) conducted their experiments at pressures of 35 to 76 cm Hg, and they judged the temperature jump effect to be negligible. In this pressure region, Vargaftik and Zimina (31) note that the temperature jump effect is large for helium, but they were unable to apply any corrections to Kannuluik and Carman's (16) work because exact values of the gas pressures at which measurements were made are not given.

The data of Peterson and Bonilla (23) cover the temperature range 306° to $1,268^{\circ}$ K. The 0° and 100° C data points of Kannuluik and Carman (16) appear to be consistent with the lower temperature results of Peterson and Bonilla (23), but disparities increase systematically with increasing temperature. At 579° K (306° C), Kannuluik and Carman's highest temperature point, the correlation equation of

Peterson and Bonilla gives a thermal conductivity value 6.25 percent larger than Kannuluik and Carman's corrected experimental measurement. Powell and coworkers' (24) statement indicating convergence of data trends for sources (16, 23) is incongruous because divergent systematic trends in the data are apparent.

Gandhi and Saxena (7), in 1968, made a critical assessment of the thermal conductivity data of helium independent of the particular efforts of TPRC. They provide smoothed recommended values of the thermal conductivity values of helium for the temperature range 73° to 793° K. They gave consideration to the uncertainties in different experimental methods and to systematic trends in data from different sources. They estimate their correlated thermal conductivity values are uncertain by about 2 to 3 percent to 473° K and about 4 percent above this temperature.

Also, Ho (13) has made a detailed literature search for the thermal conductivity values of helium, and he has compared experimental values with those quantities computed from the Lennard-Jones (6:12) and the modified Buckingham (Exp-6) potentials (12, 21). For the temperature range 100° to 1,000° K, in general, the experimental data points deviate by ± 6 percent from values computed from the (Exp-6) potential function, and larger deviations are encountered for the L-J (6:12) potential function.

Shih and Ibele (26) have used the Lennard-Jones (6:9) potential function to correlate the thermal conductivity data of helium. In the temperature range 200° to 800° K, deviations of experimental data from their computed results are about ± 4 percent.

For the temperature range 100° to 400° K, most general correlations of the thermal conductivity values of low-density helium show experimental data deviations relative to correlation equations or smoothed data values of about ± 4 percent. Therefore, Powell and coworkers' (24) assessment of 1 percent accuracy for the TPRC recommended values in this temperature range appears questionable.

Selected experimental data from sources (1, 3, 4, 9, 13-16, 19-20, 23, 25, 30-31, 36) and results from correlations (24, 29) were considered in selecting an equation to represent the temperature dependency of the low-density thermal conductivity coefficients, λ_T° of helium for the temperature range 100° to 1,200° K.

The equation

$$\lambda_T^\circ = 311.70 + 4.474T - 1.632 \times 10^{-3} T^2 + 5.0076 \times 10^{-7} T^3, \quad (3)$$

where λ_T° = thermal conductivity of helium, $\mu\text{j}/\text{cm sec } ^\circ\text{K}$,

and T = absolute temperature, $^\circ\text{K}$,

was considered to be the most suitable.

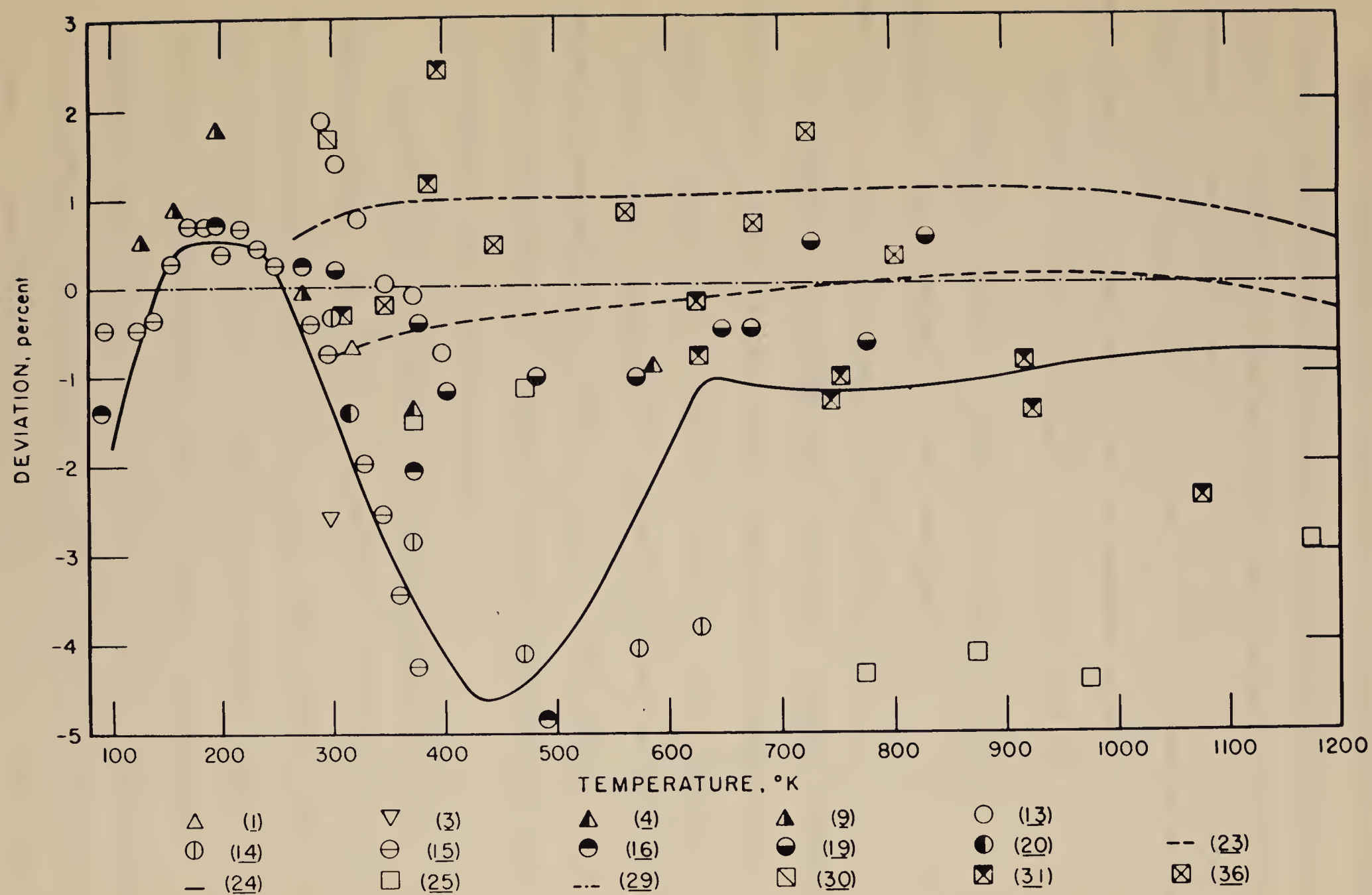
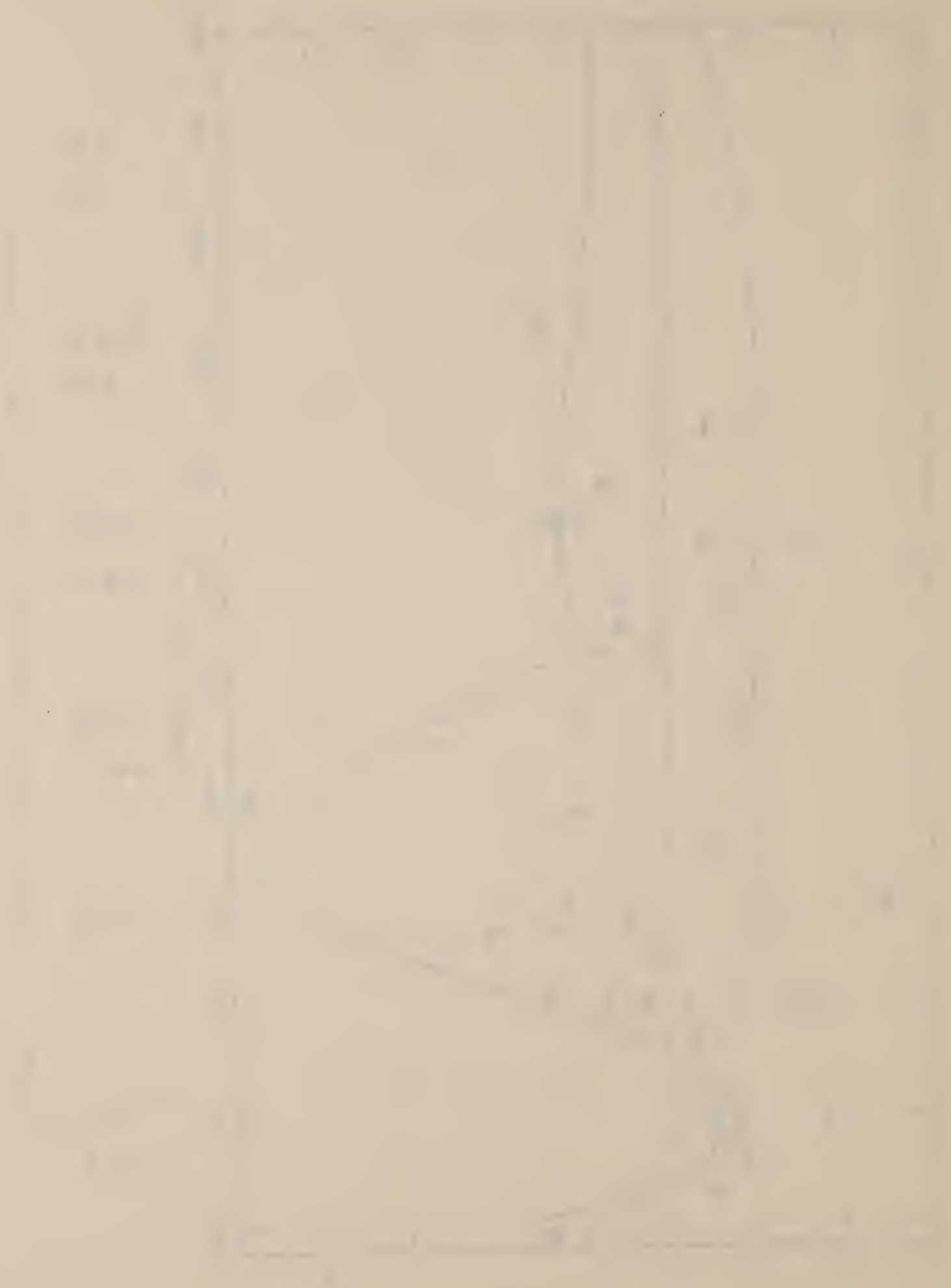


FIGURE 1—Low-Density Thermal Conductivity Deviation Plot for Helium.



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Figure 1 summarizes the deviation in the low-density thermal

FIGURE 1. - Low-Density Thermal Conductivity Deviation Plot for Helium.

conductivity values of helium when values obtained from equation 3 are compared with experimental and recommended values.

Deviation, percent, in figure 1 is represented by

$$\text{Deviation, percent} = [(\text{Exp.} - \text{Calc.}) / \text{Calc.}] \times 100, \quad (4)$$

where Exp. = value reported by an investigator,

and Calc. = the value computed from equation 3.

The departure of the NBS (24) recommended thermal conductivity coefficients of helium from values computed from equation 3 is depicted in figure 1 by a "best-fit" curve for the deviations. Also, a "best-fit" curve is provided to show the deviations between λ_T° values recommended by Tsederberg, Popov, and Morozova (29) and values computed from equation 3. Discrete deviations depart from the "best-fit" curves by less than 0.1 percent.

It can be seen from figure 1 that the experimental data of Johannin, Wilson, and Vodar (14), Johnston and Grilly (15), and Kannuluik and Carman (16) follow closely the deviation trend of NBS (24) recommended λ_T° values. Kannuluik and Carman's value for λ_T° at 579° K is 6.1 percent smaller than λ_T° computed from equation 3; therefore, this deviation is not shown on figure 1. Data from (15-16) are a part of the basis for the NBS recommended λ_T° values, but the data of Johannin and coworkers (14) are not and their data

THEORY OF THE DIFFERENTIAL CALCULUS

CHAPTER I. OF THE DIFFERENTIAL CALCULUS.

SECTION I. OF THE DIFFERENTIAL CALCULUS.

ARTICLE I. OF THE DIFFERENTIAL CALCULUS.

ARTICLE II. OF THE DIFFERENTIAL CALCULUS.

ARTICLE III. OF THE DIFFERENTIAL CALCULUS.

ARTICLE IV. OF THE DIFFERENTIAL CALCULUS.

ARTICLE V. OF THE DIFFERENTIAL CALCULUS.

ARTICLE VI. OF THE DIFFERENTIAL CALCULUS.

ARTICLE VII. OF THE DIFFERENTIAL CALCULUS.

ARTICLE VIII. OF THE DIFFERENTIAL CALCULUS.

ARTICLE IX. OF THE DIFFERENTIAL CALCULUS.

ARTICLE X. OF THE DIFFERENTIAL CALCULUS.

ARTICLE XI. OF THE DIFFERENTIAL CALCULUS.

ARTICLE XII. OF THE DIFFERENTIAL CALCULUS.

ARTICLE XIII. OF THE DIFFERENTIAL CALCULUS.

ARTICLE XIV. OF THE DIFFERENTIAL CALCULUS.

ARTICLE XV. OF THE DIFFERENTIAL CALCULUS.

ARTICLE XVI. OF THE DIFFERENTIAL CALCULUS.

ARTICLE XVII. OF THE DIFFERENTIAL CALCULUS.

ARTICLE XVIII. OF THE DIFFERENTIAL CALCULUS.

ARTICLE XIX. OF THE DIFFERENTIAL CALCULUS.

ARTICLE XX. OF THE DIFFERENTIAL CALCULUS.

ARTICLE XXI. OF THE DIFFERENTIAL CALCULUS.

ARTICLE XXII. OF THE DIFFERENTIAL CALCULUS.

require special consideration and comment. Johannin and coworkers present a thermal conductivity versus pressure graph showing five thermal-conductivity isotherms. All isotherms show a steep increase in thermal conductivity with increasing pressure for $P \leq 30$ atmospheres, a sharp change in slope in the neighborhood of 30 to 50 atmospheres, and then a much decreased gradient where further increases in the thermal conductivity are almost linear with increasing pressure. Johannin and coworkers (14) did not account for the temperature jump effect in their experiments, and Vargaftik and Zimina (31) have computed that their data (14) at $P \approx 1$ atmosphere should be corrected by +2 percent at 310.95°K and +6 percent at 588.75°K . Temperature jumps at the boundary between equipment and a test gas arise at low pressures (28) and this effect decays very rapidly with increasing pressures. Thus, for pressures between 1 and 30 atmospheres, the $\lambda = f(P)$ curves (14) cannot reflect thermal conductivity variations due to temperature jumps only and other factors should be considered for the initial large pressure dependence of the thermal conductivity measurements of Johannin and coworkers (14).

Leidenfrost (18) in a first attempt to measure the thermal conductivity coefficients of helium from 1 to 100 atmospheres at 17.4°C in a new apparatus obtained a thermal-conductivity isotherm having thermal conductivity-pressure gradients approximately the same as those observed by Johannin and coworkers (14) at 30°C .

Repeated evacuation and purgation of his apparatus with helium and a second run of the experiment produced a thermal-conductivity isotherm almost linear with pressure for the total pressure range 1 to 70 atmospheres. Although his new apparatus had been evacuated to below 1μ several times for periods to several hours prior to the first experimental run, the inconsistent results between the first and second runs of the experiment could be attributed only to impurities (water vapor and air) retained by the apparatus and present during the first run of the experiment. A thermal conductivity-pressure graph in Leidenfrost's paper shows the second run 1-atmosphere thermal conductivity value to be about 2.4 percent larger than the value obtained in the first experimental run. Johannin and coworkers (14) used a very ineffective method for purging their apparatus of impurities. We have assumed that "zero-pressure" values obtained by extrapolation of their higher pressure data to zero pressure provides λ_T° values closer to true values than their 1-atmosphere results. Zero-pressure λ_T° values, 2.51, 2.96, 3.59, 3.07 and 4.22 percent larger than their 1-atmosphere results at 300.15° , 372.15° , 471.15° , 572.65° , and 629.15° K, respectively, were obtained from extrapolations. Deviations shown on figure 1 are for the 1-atmosphere thermal conductivity values as reported by Johannin and coworkers (14).

The first thing I noticed when I stepped out of the car was the
familiarity of the air. It was the same as the air I had breathed
in the city of London. The only difference was that the air here
was cleaner. The streets were wide and the buildings were tall.
The people were friendly and the food was delicious. I had heard
that the city was beautiful and I was not disappointed. The city was
just what I needed. I had been looking for a place to live for
months and I had finally found it. The city was perfect. I had
found a place where I could live and work. I had found a place
where I could be happy. I had found a place where I could be
myself. I had found a place where I could be free. I had found
a place where I could be me.

THE END

The data of Ho (13) show an unusual hump in the low-pressure region of his lower temperature thermal-conductivity isotherms, and his results were extrapolated to zero pressure to provide λ_T° values for evaluating the constants in equation 3. The zero-pressure λ_T° values derived from his measurements above 20 atmospheres are within ± 0.86 percent of his 1-atmosphere results, except at 398.15° K where the extrapolated value is 1.51 percent larger than his 1-atmosphere value. Deviations, on figure 1, are relative to Ho's 1-atmosphere results.

The thermal conductivity measurements of Le Neindre and coworkers (19) are similar to the results obtained by Johannin and coworkers (14); thermal-conductivity isotherms show an initial large pressure dependence with increasing pressure, a sharp change in slope, and a decreased thermal conductivity-pressure gradient at higher pressures. Cognizant of Vargaftik's (31) criticism of Johannin (14) for his failure to correct his low-pressure results for the temperature jump effect, Le Neindre and coworkers (19) ran two series of experiments where gaps of 0.2 and 0.4 mm were used in a concentric cylinder apparatus. They observed the same unusual pressure dependence of the thermal conductivity of helium for both series of experiments in the pressure region 5 to 120 atmospheres. Le Neindre and coworkers (19) viewed their results from the two experiments as a confirmation of Vargaftik's (31) assumption that λ_T° values should be obtained by extrapolation of higher pressure

results to a low-pressure limit in preference to using the low-pressure values measured for λ_T° . Le Neindre and coworkers (19) attribute the unusual behavior of $\lambda = f(P)$ below 50 atmospheres to a wall effect but they do not give any details regarding this effect. They did not correct their results for the temperature jump effect. It is very unlikely that any part of the behavior of $\lambda = f(P)$ in the region 5 to 120 atmospheres is due to the temperature jump effect. Values of λ_T° at 303.15°, 403.15°, 483.15°, 572.15°, 649.15°, 675.15°, and 778.15° K extrapolated from higher pressure results obtained from the 0.2 mm gap apparatus are given by Le Neindre and coworkers (19). Their extrapolated λ_T° values are too large when they are compared with higher pressure results, and their 10 thermal-conductivity isotherms were fitted by the method of least squares to polynomials employing successively higher degree terms of gas density to the fourth degree. Intercept values obtained from second-degree equations were considered to be more representative of the λ_T° values of helium. For the seven isotherms associated with the 0.2 mm gap apparatus, intercept values from the second-degree equations are on the average 1.27 percent larger than their measurements at approximately 1 atmosphere (19), whereas Le Neindre and coworkers' extrapolated values are on an average 2.33 percent larger than their measurements in this region. Values of λ_T° obtained from intercept values of the second-degree equations were used in evaluating the constants of equation 3, and the deviations shown on figure 1 are relative to these values.

Peterson and Bonilla (23) summarized their experimental results with the equation

$$\lambda_T^\circ \times 10^5 = 0.5430 T^{0.7356}, \quad (5)$$

where $\lambda_T^\circ = \text{cal}/(\text{cm sec } ^\circ\text{K})$,

and $T = \text{temperature, } ^\circ\text{K}$,

for data covering the temperature range 306° to $1,268^\circ \text{ K}$. A probable error of 1.25 percent is given for values computed from equation 5. The agreement between values obtained from our equation 3, and their equation 5, is good as can be seen on figure 1.

Saxena and Saxena (25) determined the thermal conductivity of helium in the temperature range 350° to $1,350^\circ \text{ K}$, and give the relationship,

$$\lambda_T^\circ \times 10^5 = 17.201 + 6.674 \times 10^{-2} T - 1.25 \times 10^{-6} T^2, \quad (6)$$

where $\lambda_T^\circ = \text{cal}/(\text{cm sec } ^\circ\text{K})$,

and $T = \text{temperature, } ^\circ\text{K}$,

to represent their data. They say that equation 6 is representative of their observations with a mean absolute deviation of 0.9 percent. The agreement between values computed from equations 3 and 6 for the temperature range 350° to $1,200^\circ \text{ K}$ is poor. Values obtained from equation 6 deviate from values computed from our equation 3 by +0.3, -5.0, and -3.7 percent at 350° , 700° , and $1,200^\circ \text{ K}$, respectively. Deviations for several of Saxena and Saxena's (25) experimental measurements relative to equation 3 are shown on figure 1.

Timrot and Umanskii (27) measured the thermal conductivity of helium in the temperature range 400° to 2,400° K and have correlated their data with the equation

$$\lambda_T^\circ = 0.075 + 0.236 \times 10^{-3} T - 0.0155 \times 10^{-6} T^2, \quad (7)$$

where $\lambda_T^\circ = \text{k cal}/(\text{m hr } ^\circ\text{K})$,

and $T = \text{temperature, } ^\circ\text{K}$.

They do not present their experimental data and they do not give any statistics as to how representative equation 7 is of their measurements. They estimate that the total measurement error did not exceed 5.5 percent. Values obtained from Timrot and Umanskii, equation 7, deviate from those quantities computed from our equation 3 by +3.6, -4.9, and -7.0 percent at 400°, 800°, and 1,200° K, respectively.

The coefficients of thermal conductivity of a monatomic gas can be readily computed from viscosity data (12) in the first approximation by

$$\lambda_T^\circ = \frac{15}{4} \frac{R}{M} \eta^\circ, \quad (8)$$

where $\lambda_T^\circ = \text{dilute-gas thermal conductivity}$,

$R = \text{gas constant}$,

$M = \text{molecular weight}$,

and $\eta_T^\circ = \text{shear viscosity of the dilute gas}$.

Higher approximations to the coefficients of thermal conductivity and viscosity differ only slightly from unity, vary slowly with temperature, and can be neglected in the application of equation 8 because in the full expansion of this equation the higher approximations to λ_T° and η_T° appear as ratio which is very close to unity.

Dawe and Smith (5), DiPippo and Kestin (6), and Guevara, McInteer, and Wageman (11) have measured the viscosity coefficients of helium at high temperatures. The measurements of Dawe and Smith (5), 293.2° to 1,530° K, are relative to adopted viscosity coefficients of helium and nitrogen (196.0 and 175.7 micropoises, respectively) at 293.2° K. The measurements of Guevara and coworkers (11), 1,100° to 2,150° K are relative to an adopted viscosity for helium at 283° K (191.2 μp). The results of DiPippo and Kestin (6) are for the absolute measurement of helium viscosities in the temperature range 297.16° to 672.88° K.

Thermal conductivity coefficients computed from viscosity coefficients (5, 6) in the temperature region 350° to 550° K are inconsistent with values recommended by NBS (24) and the experimental thermal conductivity data from sources (15, 16). Discrepancies exceed 5 percent. In the temperature range 600° to 1,200° K, λ_T° values computed from η_T° values (5, 6, 11) follow closely the experimental thermal conductivity measurements of Vargaftik and Zimina (31), are within 2.7 percent of the NBS (24) recommended values, and differ, in general, appreciably from the results of

Saxena and Saxena (25) and Timrot and Umanskii (27). The thermal conductivity values from (25, 27) are much lower than λ_T° values computed from viscosity measurements.

The thermal conductivity values computed from viscosity coefficients were not used in obtaining the constants of equation 3 but were used as a guide in the rejection of experimental λ_T° data. Those experimental λ_T° values which did not fall within ± 3.5 percent of any given λ_T° value computed from a viscosity measurement were not used in obtaining the constants in equation 3. Thermal conductivity values computed from the η_T° values of Dawe and Smith (5) deviate from equation 3 values by +1.6, -0.5, -2.2, and -3.6 percent at 300°, 600°, 900°, and 1,200° K, respectively. The average deviation of the 11 λ_T° values computed from DiPippo and Kestin (6) η_T° data from equation 3 values is 1 percent. Deviations of -1.1, -1.4, and -1.5 percent at 1,100°, 1,150°, and 1,200° K, respectively, from equation 3 values are obtained from the viscosity measurements of Guevara, McInteer, and Wageman (11).

The thermal conductivity values of dilute monatomic gases can be calculated from the Chapman-Enskog theory (12). The first approximation to the thermal conductivity of a pure gas is given by the equation

$$\lambda_T^\circ \times 10^6 = \frac{832.24 (T/M)^{1/2}}{\sigma^2 \Omega(2,2)^*}, \quad (9)$$

where $\lambda_T^\circ = j/\text{cm sec } ^\circ\text{K}$,

$T = \text{temperature, } ^\circ\text{K}$,

$M = \text{molecular weight}$,

$\sigma = \text{collision diameter, A}$,

and $\Omega^{(2,2)*} = \text{collision integral values, reduced by rigid-sphere values, which are functions of the intermolecular potential and of the reduced temperature, } T^* = kT/\epsilon$.

The correct functional form of the potential energy of molecular interaction is not known, and it is customary to use empirical potential energy functions. Two empirical potential functions used for computing the transport properties of helium are--

The Lennard-Jones (L-J) (6:9) potential, which has two adjustable parameters, force constants, which are evaluated from experimental data, is given (26) by

$$\varphi(r) = \frac{27}{4} \epsilon \left[(\sigma/r)^9 - (\sigma/r)^6 \right], \quad (10)$$

where $\varphi(r)$ is the interaction potential of two molecules separated by distance, r , and ϵ is the maximum energy of attraction. At $r = \sigma$ the potential energy is zero, $\varphi = 0$.

The modified Buckingham (Exp-6) potential has three adjustable parameters. This potential is given (21) by

$$\varphi(r) = \frac{\epsilon}{1 - \frac{6}{\alpha'}} \left[\frac{6}{\alpha'} e^{\alpha' \left(1 - r/r_m\right)} - \left(\frac{r_m}{r}\right)^6 \right], \quad (11)$$

where r_m is the value of r at the energy minimum and α' is a parameter which is a measure of the steepness of the repulsive part of the function.

Tables of collision integral values for the Lennard-Jones (6:9) potential as a function of T^* are available (17, 26), and force constants ($\epsilon/k = 16.12^\circ \text{ K}$ and $\sigma = 2.571 \text{ A}$) derived from helium viscosity data for this potential are given by Shih and Ibele (26).

Mason and Rice (21) by using $\alpha' = 12.4$ obtained $\epsilon/k = 9.16^\circ \text{ K}$ and $r_m = 3.135 \text{ A}$ ($r_m \equiv \sigma$) for the "Exp-6" potential from helium viscosity data. Collision integral values for the "Exp-6" potential as a function of T^* are given by Hirschfelder, Curtiss, and Bird (12).

The independent variables in the Chapman-Enskog expressions for both η_T° and λ_T° are T , M , σ , $\Omega^{(2,2)*}$, and an arbitrary units of measurement constant. The scale relationships of $\Omega^{(2,2)*}$ which is a function of T^* change from one potential to another. The potential parameters ϵ/k and σ cannot be determined uniquely from experimental values of η_T° or λ_T° for a given potential. Optimum values of ϵ/k and σ are commonly obtained by repeated selection of ϵ/k values; computing

values of σ , for a given value of ϵ/k , from the data set of n values;

and computing $\bar{\sigma} = \left[\sum_{i=1}^n \sigma_i \right] / n$ and $\sum_{i=1}^n (\sigma_i - \bar{\sigma})^2$ for each choice of ϵ/k .

The final value of ϵ/k is selected to correspond to the minimum value for $\sum_{i=1}^n (\sigma_i - \bar{\sigma})^2$.

If a potential model is to be truly representative of the thermal conductivity data of a gas, the collision diameter, σ , in equation 9 should be independent of temperature over a wide range of temperatures. When the procedures outlined for obtaining optimum values of ϵ/k and σ from a data set are applied to the NBS (24) recommended values for λ_T° in the temperature range 100° to $1,200^\circ$ K by using the L-J (6:9) potential and $\Omega^{(2,2)*}$ values from (17), large changes in the magnitude of σ are noted for those λ_T° values in the temperature range 350° to 500° K.

Thermal conductivity values computed from equation 9 by using the L-J (6:9) and the "Exp-6" potentials with recommended force constants (21, 26) compare poorly with the λ_T° values recommended by NBS (24) for the temperature range 300° to 500° K. However, on both sides of this temperature range the agreement between computed λ_T° values and those λ_T° values recommended by NBS (24) is reasonably good. In the temperature range 300° to 500° K, λ_T° values computed from equation 9 with the L-J (6:9) and "Exp-6" potentials by using force constants (21, 26) and $\Omega^{(2,2)*}$ values (17, 12), respectively, are in good agreement, and the results from both potential models

are in good agreement with λ_T° values computed from equation 3. The correct functional form of the potential energy of interaction has eluded science and neither the L-J (6:9) nor "Exp-6" potentials may be the most physical significant potential for computing the transport properties of helium. However, both potentials provide an acceptable interpolation scheme for a large number of viscosity and thermal conductivity measurements for helium over a broad temperature range. The discordant results obtained for σ values from the NBS (24) recommended λ_T° values in the temperature range 300° to 500° K suggest that the published table values in this region may be incorrect by as much as 5 percent.

It is apparent; after considering the accuracy claimed for thermal conductivity measurements, correction applied and neglected in λ_T° determinations, systematic trends in the data of given workers, guidance received from viscosity data and kinetic theory, and results of previous transport property correlations (6-7, 13, 21, 24, 26, 29, 31, 34) for helium; that further measurements of λ_T° values for helium in the temperature region of 100° to 1,200° K are desirable.

The scatter of the low-density thermal conductivity data for helium is such that there are many possible choices for the form of an equation to represent the temperature dependence of the λ_T° values. However, equation 3 appears to be an acceptable interpolation equation to meet the engineering objectives for most heat transfer calculations in the temperature range 133° to 740° K. Uncertainties in λ_T° values computed from equation 3 may be ± 5 percent.

DENSE-GAS THERMAL CONDUCTIVITY OF HELIUM

The Enskog equation (12) and other rigid-sphere gas models for computing the thermal conductivity of dense gases have been evaluated for helium (13, 14, 19). The hard-sphere models represent the broad features of the higher temperature thermal conductivity data for helium but the quantitative agreement desired of a correlation equation is lacking.

Golubev (8) introduced the thermodynamic quantity $\left(\frac{\partial P}{\partial T}\right)_V$ to replace density in the correlation of residual viscosity, and Wood and Boone (34) used this concept to generalize the viscosity behavior of the helium-nitrogen system from 133° to 740° K for pressures to 240 atmospheres. An extension of Golubev's (8) relationship for residual viscosity to correlation of the residual thermal conductivity of nitrogen has been made by Wood, Baer, and Boone (33).

Residual thermal conductivity values, $(\lambda_{T,P} - \lambda_T^\circ)$, of helium obtained from five sources (9, 13, 14, 19-20) were used to compute values for α and β in a residual thermal conductivity expression analogous to the Golubev residual viscosity equation

$$(\lambda_{T,P} - \lambda_T^\circ) = \alpha \left[\left(\frac{\partial P}{\partial T} \right)_V \right]^\beta, \quad (12)$$

where $\lambda_{T,P}$ = thermal conductivity of the compressed gas,

λ_T° = thermal conductivity of the dilute gas,

$\left(\frac{\partial P}{\partial T}\right)_V$ = thermal pressure coefficient,

and α and β are parameters characteristic of the substance.

Thermal pressure coefficients, $\left(\frac{\partial P}{\partial T}\right)_V$, derived from the equation of state of Wood, Boone, Marshall, and Baer (35), and a general computer program for solving nonlinear regression problems written by Grout (10) gave the relationship, in microjoules/(centimeter second degree Kelvin),

$$\left(\lambda_{T,P} - \lambda_T^\circ\right) = 146.7635 \left[\left(\frac{\partial P}{\partial T}\right)_V\right]^{0.8289516}, \quad (13)$$

where $\left(\lambda_{T,P} - \lambda_T^\circ\right)$ = residual thermal conductivity, $\mu\text{j}/\text{cm sec } ^\circ\text{K}$,
and $\left(\frac{\partial P}{\partial T}\right)_V$ = atm/ $^\circ\text{K}$.

Table 1 shows the data distribution and average absolute deviation between the computed and experimental thermal conductivity values of various investigators. Table 2 is provided to show the maximum deviations between computed and experimental thermal conductivity values. For all comparisons in tables 1 and 2, computed thermal conductivity values, $\lambda_{T,P}$, were obtained by using λ_T° values computed from equation 3 in equation 13, and all comparisons are relevant to experimental data as reported by investigators, except for Le Neindre and coworkers (19) where comparisons were made with low-pressure λ values extrapolated from higher pressure measurements. Thermal

TABLE 1. - Data distribution and deviation analysis

Source of data	T, °K	Pressure range, atm	No. of points	$\frac{\sum \text{Pct Dev} }{N}$ ^{1/}
Golubev and Shpagina (9)	126.55	1.0 - 485.00	34	0.94
Do	157.45	1.0 - 485.00	22	.47
Do	195.15	1.0 - 485.00	30	1.36
Do	273.65	1.0 - 485.00	35	.64
Total and average			121	.87
Ho (13)	290.65	1.0 - 140.00	9	1.43
Do	293.15	1.0 - 300.00	17	.99
Do	298.15	1.0 - 100.00	7	1.25
Do	303.15	1.0 - 100.00	7	1.03
Do	323.15	1.0 - 100.00	7	.53
Do	348.15	1.0 - 120.00	8	.17
Do	373.15	1.0 - 120.00	8	.21
Do	398.15	1.0 - 80.00	6	.79
Total and average			69	.83
Johannin, Wilson, and Vodar (14) .	300.15	1.0 - 204.00	16	.65
Do	372.15	1.0 - 228.60	12	.61
Do	471.15	1.0 - 200.10	12	1.50
Do	572.65	1.0 - 221.70	11	1.75
Do	629.15	1.0 - 201.10	10	.61
Total and average			61	1.00
Le Neindre and others (19)	303.15	(2/) - 499.38	38	.53
Do	378.15	(2/) - 117.44	9	.37
Do	403.15	(2/) - 504.32	11	.87
Do	483.15	(2/) - 496.42	15	.67
Do	572.15	(2/) - 439.18	7	.71
Do	649.15	(2/) - 496.42	13	.53
Do	675.15	(2/) - 494.45	5	.42
Do	729.15	(2/) - 124.35	6	.60
Do	778.15	(2/) - 498.40	10	.22
Do	831.15	(2/) - 124.35	6	.28
Total and average			120	.54
Lenoir and Comings (20)	315.93	1.0 - 205.20	9	.86
Peterson, Hahn, and Comings (22) .	348.15	50.0 - 500.00	5	1.78
TOTAL AND AVERAGE, all observations			385	.79

^{1/} Mean absolute percent deviation.^{2/} Low-density thermal conductivity values obtained by extrapolation from values at higher pressures.

TABLE 2. - Maximum deviations between computed and experimental thermal conductivities

Source of data	T, °K	P, atm	$\lambda_{Exp.}$	$\lambda_{Comp.}$	Deviation, percent
			$\mu j/cm \text{ sec } ^\circ K$		
Golubev and Shpagina (9)	126.55	25.20	858.00	891.39	-3.75
Do	157.45	97.79	1088.00	1076.60	1.06
Do	195.15	291.40	1364.00	1329.02	2.63
Do	273.65	73.59	1451.00	1473.28	-1.51
Ho (13)	290.65	10.00	1530.00	1495.48	2.31
Do	293.15	10.00	1538.00	1504.54	2.22
Do	298.15	10.00	1552.00	1522.61	1.93
Do	303.15	10.00	1568.00	1540.64	1.78
Do	323.15	10.00	1626.00	1612.17	.86
Do	348.15	10.00	1707.00	1700.37	.39
Do	373.15	20.00	1800.00	1792.91	.40
Do	398.15	40.00	1904.00	1887.71	.86
Johannin, Wilson, and Vodar (14) . .	300.15	38.80	1571.90	1547.95	1.55
Do	372.15	1.00	1725.90	1777.57	-2.91
Do	471.15	1.00	2023.40	2110.62	-4.13
Do	572.65	1.00	2334.30	2433.35	-4.07
Do	629.15	1.00	2506.20	2605.93	-3.83
Le Neindre and others (19)	303.15	499.38	1777.00	1748.61	1.62
Do	378.15	98.69	1830.00	1845.15	-.82
Do	403.15	504.32	2086.00	2054.98	1.51
Do	483.15	410.56	2300.00	2274.27	1.13
Do	572.15	439.18	2575.00	2546.45	1.12
Do	649.15	74.02	2662.00	2689.44	-1.02
Do	675.15	204.29	2780.00	2796.54	-.59
Do	729.15	68.10	2943.00	2920.88	.76
Do	778.15	33.56	3028.00	3051.71	-.78
Do	831.15	33.56	3217.00	3200.63	.51
Lenoir and Comings (20)	315.93	205.20	1708.10	1679.51	1.70
Peterson, Hahn, and Comings (22) . .	348.15	50.00	1674.00	1721.93	-2.78

conductivity values of helium computed from equation 13 utilizing equation 3 are presented in table 3, and figure 2 shows the isobaric

FIGURE 2. - Thermal Conductivity of Helium.

variation of the thermal conductivities with temperature.

PRANDTL NUMBERS OF HELIUM

Prandtl numbers, $C_p \eta / \lambda$, of helium were computed by incorporating the thermodynamic equations presented by Wood (32) for computing isobaric specific heat, C_p , values of helium from the equation of state of Wood and coworkers (35) and equations 3 and 13 of this work into the Fortran program of Wood and Boone (34) for computing viscosities of helium.

The relationship for the viscosity of helium (34),

$$\eta_{T,P} = \eta_T^\circ + 2.5254571 \left[\left(\frac{\partial P}{\partial T} \right)_V \right]^{1.8698618}, \quad (14)$$

where $\eta_T^\circ = 4.2605563 T^{0.67362904}$,

T = temperature, °K,

and $\eta_{T,P}$ = viscosity of compressed helium, micropoises, μp ,

represented 354 experimental viscosity values of helium in the temperature range 183.15° to 918.52° K for pressures to 546.7 atmospheres with a mean absolute deviation of 0.78 percent. The maximum deviation between a computed and an experimental value was 4.57 percent for a point at 517.15° K and 127.0 atmospheres.

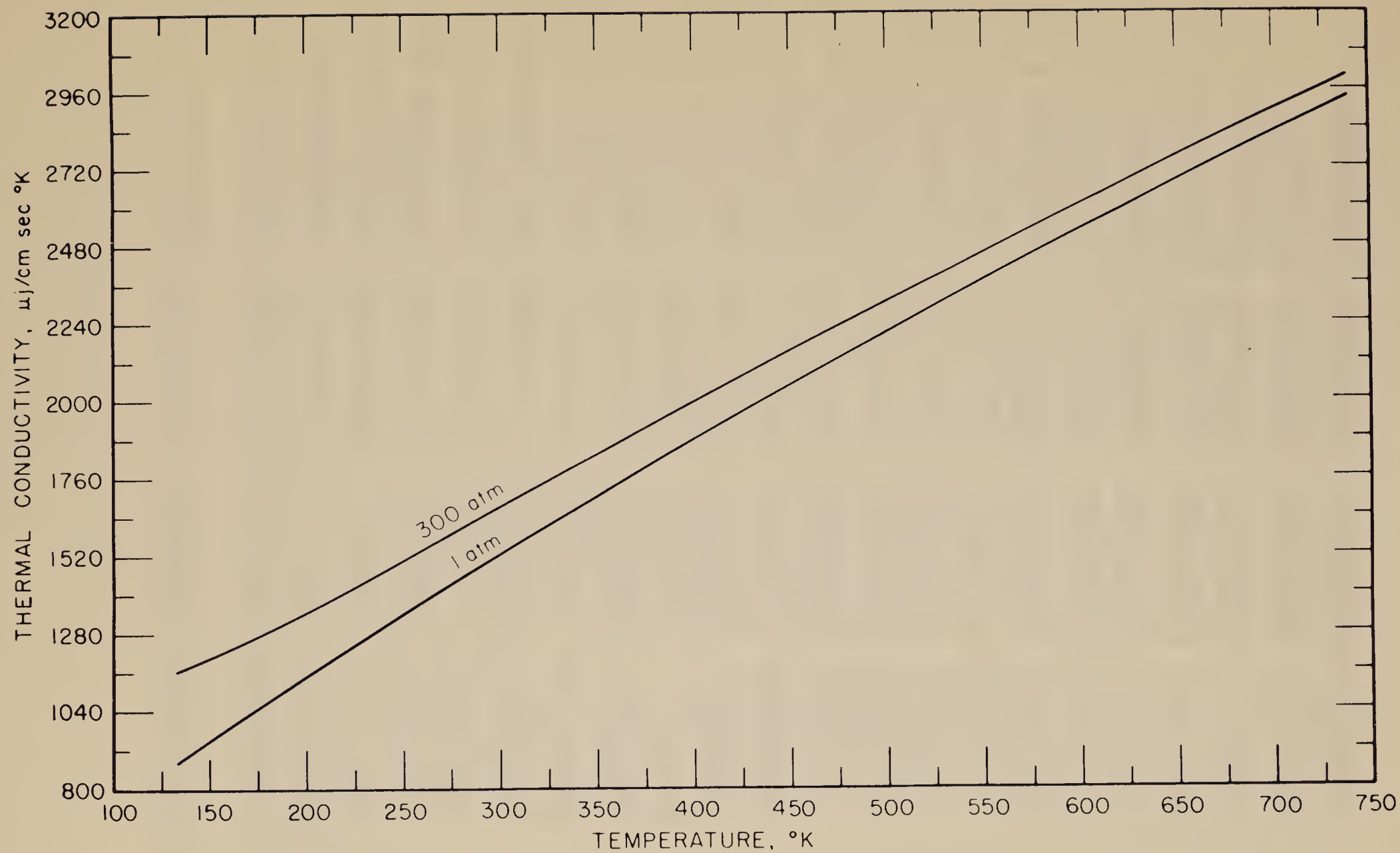


FIGURE 2. - Thermal Conductivity of Helium.

FEB 9 1971

TABLE 3. - THERMAL CONDUCTIVITY OF HELIUM

		μJ/CM SEC °K																					
T, DEG K		310	320	330	340	350	360	370	380	390	400	410	420	430	440	450	460	470	480	490	500	510	520
P, ATM		TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC
1		1558	1594	1630	1665	1700	1735	1770	1805	1839	1873	1907	1941	1975	2008	2041	2074	2107	2139	2172	2204	2236	2268
5		1562	1597	1633	1668	1703	1738	1773	1808	1842	1876	1910	1944	1977	2011	2044	2077	2109	2142	2174	2207	2239	2270
10		1565	1601	1636	1672	1707	1742	1776	1811	1845	1879	1913	1947	1980	2013	2046	2079	2112	2145	2177	2209	2241	2273
15		1569	1604	1640	1675	1710	1745	1779	1814	1848	1882	1916	1949	1983	2016	2049	2082	2114	2147	2179	2211	2243	2275
20		1572	1607	1643	1678	1713	1748	1782	1816	1851	1884	1918	1952	1985	2018	2051	2084	2117	2149	2181	2213	2245	2277
25		1575	1610	1646	1681	1716	1750	1785	1819	1853	1887	1921	1954	1987	2021	2053	2086	2119	2151	2183	2216	2247	2279
30		1578	1613	1648	1683	1718	1753	1787	1821	1856	1889	1923	1956	1990	2023	2056	2088	2121	2153	2185	2218	2249	2281
35		1581	1616	1651	1686	1721	1755	1790	1824	1858	1892	1925	1959	1992	2025	2058	2090	2123	2155	2187	2219	2251	2283
40		1584	1619	1654	1689	1723	1758	1792	1826	1860	1894	1927	1961	1994	2027	2060	2092	2125	2157	2189	2221	2253	2285
45		1586	1621	1656	1691	1726	1760	1795	1829	1862	1896	1930	1963	1996	2029	2062	2094	2127	2159	2191	2223	2255	2287
50		1589	1624	1659	1694	1728	1763	1797	1831	1865	1898	1932	1965	1998	2031	2064	2096	2129	2161	2193	2225	2257	2288
55		1592	1627	1662	1696	1731	1765	1799	1833	1867	1900	1934	1967	2000	2033	2066	2098	2131	2163	2195	2227	2258	2290
60		1594	1629	1664	1699	1733	1767	1801	1835	1869	1903	1936	1969	2002	2035	2068	2100	2133	2165	2197	2229	2260	2292
65		1597	1632	1666	1701	1735	1770	1804	1837	1871	1905	1938	1971	2004	2037	2070	2102	2134	2166	2198	2230	2262	2293
70		1599	1634	1669	1703	1738	1772	1806	1840	1873	1907	1940	1973	2006	2039	2071	2104	2136	2168	2200	2232	2264	2295
75		1602	1637	1671	1706	1740	1774	1808	1842	1875	1909	1942	1975	2008	2041	2073	2106	2138	2170	2202	2234	2265	2297
80		1604	1639	1674	1708	1742	1776	1810	1844	1877	1911	1944	1977	2010	2043	2075	2107	2140	2172	2204	2235	2267	2298
85		1607	1641	1676	1710	1744	1778	1812	1846	1879	1913	1946	1979	2012	2044	2077	2109	2141	2173	2205	2237	2268	2300
90		1609	1644	1678	1712	1746	1780	1814	1848	1881	1915	1948	1981	2013	2046	2079	2111	2143	2175	2207	2239	2270	2301
95		1611	1646	1680	1715	1749	1783	1816	1850	1883	1917	1950	1983	2015	2048	2080	2113	2145	2177	2208	2240	2272	2303
100		1614	1648	1683	1717	1751	1785	1818	1852	1885	1918	1952	1984	2017	2050	2082	2114	2146	2178	2210	2242	2273	2305
105		1616	1651	1685	1719	1753	1787	1820	1854	1887	1920	1953	1986	2019	2051	2084	2116	2148	2180	2212	2243	2275	2306
110		1619	1653	1687	1721	1755	1789	1822	1856	1889	1922	1955	1988	2021	2053	2085	2118	2150	2182	2213	2245	2276	2308
115		1621	1655	1689	1723	1757	1791	1824	1858	1891	1924	1957	1990	2022	2055	2087	2119	2151	2183	2215	2246	2278	2309
120		1623	1657	1691	1725	1759	1793	1826	1860	1893	1926	1959	1992	2024	2057	2089	2121	2153	2185	2216	2248	2279	2311
125		1625	1660	1694	1727	1761	1795	1828	1862	1895	1928	1961	1993	2026	2058	2091	2123	2155	2186	2218	2249	2281	2312
130		1628	1662	1696	1730	1763	1797	1830	1863	1897	1930	1962	1995	2028	2060	2092	2124	2156	2188	2220	2251	2282	2313
135		1630	1664	1698	1732	1765	1799	1832	1865	1898	1931	1964	1997	2029	2062	2094	2126	2158	2189	2221	2252	2284	2315
140		1632	1666	1700	1734	1767	1801	1834	1867	1900	1933	1966	1999	2031	2063	2095	2127	2159	2191	2223	2254	2285	2316
145		1634	1668	1702	1736	1769	1803	1836	1869	1902	1935	1968	2000	2033	2065	2097	2129	2161	2193	2224	2255	2287	2318
150		1636	1670	1704	1738	1771	1805	1838	1871	1904	1937	1969	2002	2034	2067	2099	2131	2162	2194	2226	2257	2288	2319
155		1639	1672	1706	1740	1773	1807	1840	1873	1906	1938	1971	2004	2036	2068	2100	2132	2164	2196	2227	2258	2290	2321
160		1641	1675	1708	1742	1775	1808	1842	1875	1907	1940	1973	2005	2038	2070	2102	2134	2165	2197	2229	2260	2291	2322
165		1643	1677	1710	1744	1777	1810	1843	1876	1909	1942	1975	2007	2039	2071	2103	2135	2167	2199	2230	2261	2292	2323
170		1645	1679	1712	1746	1779	1812	1845	1878	1911	1944	1976	2009	2041	2073	2105	2137	2169	2200	2231	2263	2294	2325
175		1647	1681	1714	1748	1781	1814	1847	1880	1913	1945	1978	2010	2043	2075	2107	2138	2170	2202	2233	2264	2295	2326
180		1649	1683	1716	1750	1783	1816	1849	1882	1915	1947	1980	2012	2044	2076	2108	2140	2172	2203	2234	2266	2297	2328
185		1651	1685	1718	1752	1785	1818	1851	1884	1916	1949	1981	2014	2046	2078	2110	2141	2173	2204	2236	2267	2298	2329
190		1653	1687	1720	1753	1787	1820	1853	1885	1918	1951	1983	2015	2047	2079	2111	2143	2174	2206	2237	2268	2299	2330
195		1656	1689	1722	1755	1788	1821	1854	1887	1920	1952	1985	2017	2049	2081	2113	2144	2176	2207	2239	2270	2301	2332
200		1658	1691	1724	1757	1790	1823	1856	1889	1921	1954	1986	2018	2050	2082	2114	2146	2177	2209	2240	2271	2302	2333
210		1662	1695	1728	1761	1794	1827	1860	1892	1925	1957	1989	2022	2054	2085	2117	2149	2180	2212	2243	2274	2305	2336
220		1666	1699	1732	1765	1798	1831	1863	1896	1928	1960	1993	2025	2057	2089	2120	2152	2183	2214	2246	2277	2308	2338
230		1670	1703	1736	1769	1801	1834	1867	1899	1931	1964	1996	2028	2060	2092	2123	2155	2186	2217	2248	2279	2310	2341
240		1674	1707	1740	1772	1805	1838	1870	1902	1935	1967	1999	2031	2063	2095	2126	2158	2189	2220	2251	2282	2313	2344
250		1678	1711	1743	1776	1809	1841	1874	1906	1938	1970	2002	2034	2066	2097	2129	2160	2192	2223	2254	2285	2316	2346
300		1697	1730	1762	1794	1826	1858	1890	1922	1954	1986	2018	2049	2081	2112	2143	2174	2205	2236	2267	2298	2328	2359

The variation of the isobaric specific heat, $C_p = \left(\frac{\partial H}{\partial T} \right)_p$, is a function of the second derivative of the PVT surface, and a common fault of closed equations of state is that they yield C_p values which are not in good agreement with experimental results. Isobaric specific heat values (32) derived from the equation of state of Wood and coworkers (35) are within 0.60 percent of those quantities obtained from flow calorimetry in the temperature range 127.13° to 285.17° K for pressures to 136 atmospheres. Unfortunately, the accuracy of the C_p values computed cannot be substantiated at all conditions applied in obtaining the Prandtl numbers of helium because of the lack of suitable experimental data. In the temperature range 130° to 760° K for pressures to 300 atmospheres, the equation of state contributions to the isobaric specific heats are not large and the uncertainty in calculated C_p values should not be more than 1 percent. Tabular values of the Prandtl numbers are presented in table 4.

The isobaric specific heat, C_p° , of helium per unit mass at zero pressure can be taken as $5R/2M$, equation 8 may be rearranged to yield $\eta_T^\circ/\lambda_T^\circ = 4M/15R$, and by definition $P_r^\circ = C_p^\circ \eta_T^\circ/\lambda_T^\circ$; therefore, the classical kinetic theory predicts that the dilute-gas Prandtl number for helium is equal to $2/3$. The maximum deviation between any 1-atmosphere pressure Prandtl number of helium in table 4 and

TABLE 4. - PRANDTL NUMBERS OF HELIUM

T, DEG K	130	175	220	265	310	355	400	445	490	535	580	625	670	715	760
P, ATM	PRANDTL NUMBERS														
1	0.676	0.684	0.684	0.681	0.677	0.673	0.669	0.665	0.661	0.658	0.655	0.652	0.650	0.648	0.645
5	0.671	0.681	0.682	0.679	0.676	0.672	0.668	0.664	0.660	0.657	0.654	0.652	0.649	0.647	0.645
10	0.666	0.677	0.679	0.677	0.674	0.670	0.666	0.663	0.659	0.656	0.654	0.651	0.649	0.646	0.644
15	0.661	0.674	0.677	0.676	0.673	0.669	0.665	0.662	0.659	0.656	0.653	0.650	0.648	0.646	0.644
20	0.657	0.671	0.675	0.674	0.671	0.668	0.665	0.661	0.658	0.655	0.652	0.650	0.648	0.645	0.643
25	0.654	0.669	0.673	0.673	0.670	0.667	0.664	0.660	0.657	0.654	0.652	0.649	0.647	0.645	0.643
30	0.650	0.666	0.671	0.671	0.669	0.666	0.663	0.660	0.657	0.654	0.651	0.649	0.647	0.645	0.643
35	0.647	0.664	0.669	0.670	0.668	0.665	0.662	0.659	0.656	0.653	0.651	0.648	0.646	0.644	0.642
40	0.643	0.662	0.668	0.668	0.667	0.664	0.661	0.658	0.655	0.653	0.650	0.648	0.646	0.644	0.642
45	0.640	0.659	0.666	0.667	0.666	0.663	0.661	0.658	0.655	0.652	0.650	0.647	0.645	0.643	0.641
50	0.637	0.657	0.665	0.666	0.665	0.663	0.660	0.657	0.654	0.652	0.649	0.647	0.645	0.643	0.641
55	0.634	0.655	0.663	0.665	0.664	0.662	0.659	0.656	0.654	0.651	0.649	0.647	0.644	0.642	0.641
60	0.631	0.653	0.662	0.664	0.663	0.661	0.658	0.656	0.653	0.651	0.648	0.646	0.644	0.642	0.640
65	0.629	0.651	0.660	0.662	0.662	0.660	0.658	0.655	0.653	0.650	0.648	0.646	0.644	0.642	0.640
70	0.626	0.650	0.659	0.661	0.661	0.659	0.657	0.655	0.652	0.650	0.647	0.645	0.643	0.641	0.639
75	0.624	0.648	0.657	0.660	0.660	0.659	0.656	0.654	0.652	0.649	0.647	0.645	0.643	0.641	0.639
80	0.621	0.646	0.656	0.659	0.659	0.658	0.656	0.653	0.651	0.649	0.647	0.644	0.642	0.640	0.639
85	0.619	0.644	0.655	0.658	0.658	0.657	0.655	0.653	0.651	0.648	0.646	0.644	0.642	0.640	0.638
90	0.617	0.643	0.653	0.657	0.658	0.656	0.655	0.652	0.650	0.648	0.646	0.644	0.642	0.640	0.638
95	0.614	0.641	0.652	0.656	0.657	0.656	0.654	0.652	0.650	0.647	0.645	0.643	0.641	0.639	0.638
100	0.612	0.639	0.651	0.655	0.656	0.655	0.653	0.651	0.649	0.647	0.645	0.643	0.641	0.639	0.637
105	0.610	0.638	0.650	0.654	0.655	0.654	0.653	0.651	0.649	0.646	0.644	0.642	0.640	0.639	0.637
110	0.608	0.636	0.649	0.653	0.654	0.654	0.652	0.650	0.648	0.646	0.644	0.642	0.640	0.638	0.636
115	0.606	0.635	0.647	0.652	0.654	0.653	0.652	0.650	0.648	0.646	0.644	0.642	0.640	0.638	0.636
120	0.604	0.634	0.646	0.651	0.653	0.652	0.651	0.649	0.647	0.645	0.643	0.641	0.639	0.638	0.636
125	0.603	0.632	0.645	0.651	0.652	0.652	0.651	0.649	0.647	0.645	0.643	0.641	0.639	0.637	0.635
130	0.601	0.631	0.644	0.650	0.651	0.651	0.650	0.648	0.646	0.644	0.642	0.640	0.639	0.637	0.635
135	0.599	0.629	0.643	0.649	0.651	0.651	0.649	0.648	0.646	0.644	0.642	0.640	0.638	0.636	0.635
140	0.598	0.628	0.642	0.648	0.650	0.650	0.649	0.647	0.645	0.643	0.642	0.640	0.638	0.636	0.634
145	0.596	0.627	0.641	0.647	0.649	0.649	0.648	0.647	0.645	0.643	0.641	0.639	0.638	0.636	0.634
150	0.595	0.626	0.640	0.646	0.649	0.649	0.648	0.646	0.645	0.643	0.641	0.639	0.637	0.635	0.634
155	0.593	0.625	0.639	0.646	0.648	0.648	0.647	0.646	0.644	0.642	0.640	0.639	0.637	0.635	0.633
160	0.592	0.623	0.638	0.645	0.647	0.648	0.647	0.645	0.644	0.642	0.640	0.638	0.636	0.635	0.633
165	0.591	0.622	0.637	0.644	0.647	0.647	0.646	0.645	0.643	0.642	0.640	0.638	0.636	0.634	0.633
170	0.589	0.621	0.636	0.643	0.646	0.647	0.646	0.645	0.643	0.641	0.639	0.638	0.636	0.634	0.632
175	0.588	0.620	0.635	0.643	0.645	0.646	0.645	0.644	0.642	0.641	0.639	0.637	0.635	0.634	0.632
180	0.587	0.619	0.635	0.642	0.645	0.645	0.645	0.644	0.642	0.640	0.639	0.637	0.635	0.633	0.632
185	0.586	0.618	0.634	0.641	0.644	0.645	0.644	0.643	0.642	0.640	0.638	0.637	0.635	0.633	0.631
190	0.585	0.617	0.633	0.640	0.644	0.644	0.644	0.643	0.641	0.640	0.638	0.636	0.634	0.633	0.631
195	0.584	0.616	0.632	0.640	0.643	0.644	0.643	0.642	0.641	0.639	0.638	0.636	0.634	0.632	0.631
200	0.583	0.615	0.631	0.639	0.642	0.643	0.643	0.642	0.640	0.639	0.637	0.635	0.634	0.632	0.630
205	0.582	0.614	0.631	0.638	0.642	0.643	0.643	0.642	0.640	0.639	0.637	0.635	0.633	0.632	0.630
210	0.581	0.613	0.630	0.638	0.641	0.642	0.642	0.641	0.640	0.638	0.636	0.635	0.633	0.631	0.630
220	0.579	0.612	0.628	0.637	0.640	0.641	0.641	0.640	0.639	0.637	0.636	0.634	0.633	0.631	0.629
230	0.578	0.610	0.627	0.635	0.639	0.640	0.640	0.640	0.638	0.637	0.635	0.634	0.632	0.630	0.629
240	0.576	0.609	0.626	0.634	0.638	0.640	0.640	0.639	0.638	0.636	0.634	0.633	0.631	0.630	0.628
250	0.575	0.607	0.624	0.633	0.637	0.639	0.639	0.638	0.637	0.635	0.634	0.632	0.631	0.629	0.627
275	0.573	0.604	0.621	0.630	0.635	0.636	0.637	0.636	0.635	0.634	0.632	0.631	0.629	0.628	0.626
300	0.572	0.601	0.619	0.628	0.632	0.634	0.635	0.634	0.633	0.632	0.631	0.629	0.628	0.626	0.624

and theoretical value of $2/3$ is about 3 percent. Deviations of the 1-atmosphere values from the theoretical value are very likely due to uncertainties in η_T° and λ_T° values computed from the empirical equation used to represent these transport properties. A maximum uncertainty of ± 10 for the Prandtl numbers was computed from the estimated maximum uncertainties in C_p , η , and λ .

DISCUSSION

Deviations between computed and experimental thermal conductivity coefficients of compressed helium are, for the most part, of the order of 1 to 2 percent, and the correlation equations presented should be suitable for the prediction of thermal conductivity coefficients of helium in areas not covered by experiment in the temperature region 133° to 740° K for pressures to 300 atmospheres. However, the estimated reliability of computed values should not be taken as better than the actual deviations between measured and computed thermal conductivity coefficients, and uncertainties in computed values may be as much as ± 5 percent.

Recent low-density viscosity and thermal conductivity measurements for helium cast doubt on the 1 percent accuracy claimed for some of the thermal conductivity coefficients recommended by the National Bureau of Standards (24) in the temperature range of 100° to 400° K, and published values may be incorrect by as much as 5 percent. The NBS (24) recommended values are based on measurements

available to 1966 and undoubtedly the National Bureau of Standards will revise their previous recommendation in light of the new data available and as more complete information becomes available.

Discrepancies in the reported thermal conductivity data of various investigators indicate uncertainties in thermal conductivity coefficients are from 2 to 5 times, and more, than that of the estimated precision of measurement.

Discrepancies in measurements of various investigators and the fact that experimental uncertainties for the various methods of measurement are not known with equal confidence show that more accurate measurements of the thermal conductivity of helium are desirable.

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